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# Novel Algorithm for Nonlinear Distortion Reduction Based on Clipping and Compressive Sensing in OFDM/OQAM System

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**ABSTRACT-** Orthogonal Frequency Division Multiplexing with Offset Quadrature Amplitude Modulation (OFDM/OQAM) signal has high peak-to-average power ratio (PAPR) problem. It not only affects the distortion in High Power Amplifier (HPA) but also results in bit error ratio (BER) degradation. In this paper an improved algorithm based on Clipping and Compressed Sensing (CS) is proposed. The transmitter uses clipping to reduce the PAPR and, the receiver uses an improved inverse model, to reduce the nonlinear distortion introduced by HPA and CS cancels the signal distortion introduced by clipping. Simulation results show that the proposed method not only significantly reduces the PAPR of OFDM/OQAM signals, but also effectively improves the BER performance of the system.

**Keywords:** BER, Clipping, CS, HPA, OFDM/OQAM, PAPR.

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## 1. INTRODUCTION

Most commonly used multicarrier modulation method is orthogonal frequency division multiplexing (OFDM), has been utilized extensively in numerous broadband communication systems [1]. Multicarrier communications have been the subject of a lot of recent research. By reducing the frequency spectrum into small bins known as subcarriers, this communication makes use of the broad range of wideband communications [2]. These subcarriers are used to transfer data. These many subcarriers are preferably orthogonal to ensure proper recovery of the sent data. OFDM and multicarrier communication are examined in [3]. The Internet of Things (IoT) and the 5G technology standard promise improved communication systems [4-9]. High data speeds and flexibility at the lowest 5G layer are just two of the important requirements for the efficiency expected from such systems [12-14]. Using waveforms capable of effectively permitting multiple access is crucial to meeting these needs in future wireless communication systems [9]. Currently, 4G networks employ OFDM. One of the main issues with the current broadband high-speed wireless communication system is the inter-symbol interference (ISI) caused by multipath fading channels [15]. By breaking up a single frequency-selective channel into several parallel frequency flat sub-channels, OFDM reduces the impact of the ISI issue [16].

OFDM/OQAM is widely used in wireless communication systems due to its efficient spectrum utilization and anti-fading capabilities [17]. However, OFDM/OQAM signals have a higher peak-to-average power ratio (PAPR), which leads to the in-band noise generation by passing it through power amplifiers (HPA) and will reduce the operating efficiency of the HPA and the in-band distortions. The signal generates severe non-linear distortion, which degrades the bit error ratio (BER) performance of the system. To improve the working efficiency of HPA and to reduce the non-linear distortion of the signal, the PAPR reduction and the non-linear distortion compensation methods are wide research areas. The advantages and disadvantages of the widely used OFDM were analyzed by Banelli et al. [18] along with potential waveform improvements. The authors measured waveforms using numerical examples and receiver and transmitter limitations. The PAPR and BER, SNR were calculated. The PAPR reduction methods [19-21] are classified into three types: clipping, coding, and probability [22-23]. The clipping [24-25] is the simplest and most direct. However, the clipping method itself will introduce additional signal distortion [26], and it will degrade the system's BER performance. The Compressive Sensing (CS) algorithms proposed in literature [27-29] reserve the empty subcarriers, these algorithms need to reserve the empty subcarriers in advance as observation vectors, which reduces the data transmission efficiency. In literature [10] an improved CS algorithm is proposed, which selects the part affected by noise as the observation vector from the data subcarriers and uses the CS algorithm to reconstruct the clipped noise signal. This algorithm needs reserve empty subcarriers, thereby reducing the data transmission efficiency. However, this article only considers the effective compensation of the nonlinear distortion of the clipping method and does not consider the distortion effect introduced by HPA [30]. On the other hand, the compensation at the receiver can effectively reduce the nonlinear distortion introduced by HPA. In literature [31], a nonlinear distortion compensation algorithm based on the inverse HPA model is proposed. Although this method can effectively improve the BER performance of the system. However, the algorithm needs to select appropriate compensation thresholds through multiple simulations, which brings inconvenience to the hardware implementation. Moreover, the transmitter does not reduce the PAPR of the OFDM/OQAM signal [32,36]. The dynamic range required by the HPA is large and the work efficiency is not high [21,33]. To overcome the above problems, in this paper an improved distortion compensation algorithm on clipping is proposed, based on HPA inverse model compensation and CS algorithm. At the transmitter, the PAPR of the OFDM/OQAM signal is reduced by clipping to improve the working efficiency of the HPA. At the receiver, the threshold of the HPA inverse model compensator is uniquely determined according to the clipping threshold [21]. There is no need to select the threshold through multiple simulations. After compensating for the nonlinear distortion introduced by HPA, the signal distortion introduced by clipping is cancelled by CS.

Following is an outline for this article. OFDM/OQAM System, clipping method, and compressive sensing technique are discussed in *Section 2*. In *Section 3*, Non-linear distortion compensation algorithm is discussed. *Section 4* illustrates the simulation results. Finally, conclusions will be provided in *Section 5*.

## 2. OFDM/OQAM SYSTEM

OFDM/OQAM signal has the disadvantage of PAPR [33-36]. The power amplifier at the transmitter will cause severe non-linear distortion to the OFDM/OQAM signal, and affect the system's BER performance, solid-state power amplifier [11, 31] (SPA) is one of the commonly used amplifiers.

### 2.1 Impact of Power Amplifier

The Rapp's model is often used to simulate the nonlinear characteristics of the SPA amplifier. In this model, the input signal *x* and the output signal *y* are sampled as:

$$y(n) = \rho(n)e^{i\phi(n)} \tag{1}$$

Where,

$\rho(n) = |x(n)|$ Indicates the amplitude and phase is $\phi(n) = \tan^{-1}\left(\frac{y(n)}{x(n)}\right)$.

The time variable n for $\rho$ and $\phi$ can be represented as

$$u(n) = F_a(\rho)e^{jF_p(\rho)}e^{i\phi} = S(\rho)e^{i\phi}$$

Where, $F_a(\rho)$, $F_p(\rho)$ are the AM/AM, AM/PM characteristic of the HPA and $S(\rho)$ is the complex envelop of the $u(n)$ signal, its non-linear characteristics is written as follows:

$$\begin{cases} F_a(\rho) = \dfrac{\rho}{\left(1+\left(\dfrac{\rho}{A_o}\right)^{2p}\right)^{\frac{1}{2p}}} \\ F_p(\rho) = 0 \end{cases} \tag{2}$$

*From (2)* $\rho$ is the smoothing factor, $A_o$ is the maximum output determined by the input saturation $A_{sat}$ and $A_{sat}$ is determined by the input back-Off (IBO) that is:

$$IBO = 10\log_{10}\left(\frac{A_{sat}^2}{P_{in}}\right) \tag{3}$$

Where in (3), $P_{in}$ represents the average power of the amplifier input signal.

### 2.2 Clipping and Compression Sensing

The time domain signal $x_1$ after clipping the original OFDM/OQAM signal is expressed as equation (4):

$$x_1(n) = \begin{cases} x(n); & for \ \ x(n) \le A \\ Ae^{j\phi}; & for \ \ x(n) > A \end{cases} \tag{4}$$

Where, *A* represents the clipping threshold determined by the clipping ratio *γ*, i.e.

$$A = \gamma\, E\{x(n)\} \tag{5}$$

It is known from equation (4) that the clipped signal $x_1(n)$ can be expressed as the sum of the original OFDM/OQAM signal $x(n)$ and the clipping noise $c(n)$, which is:

$$x_1(n) = x(n) + c(n); \ \left(0 \le n \le (M+L-1)\right) \tag{6}$$

If it is necessary to use CS technology to reconstruct the clipped distortion signal (6), the distorted signal must meet the sparsity characteristics. To reconstruct the clipped distorted signal using CS method, the distorted signal must meet the sparsity characteristics.

According to [18], the lower the clipping ratio *γ*, the more the number of non-zero elements in the clipped noise signal *c*, and the level of sparsity. The lower, the sparsity level is measured by the sparsity *K*, and the relationship with *γ* is:

$$K = E\left\{|c|_0\right\} = Ne^{-\gamma^2} \tag{7}$$

The CS technique is introduced at the receiver using (7) is to reconstruct the clipped noise signal to effectively reduce the influence of clipped noise on BER performance. Many algorithms based on compression sensing is proposed in the literature, among them Matching Pursuit(MP) algorithms better balance the efficiency and reconstruction quality of compression algorithms, orthogonal matching Pursuit(OMP) algorithm is the most typical of the MP algorithm.

## 3. NON - LINEAR DISTORTION COMPENSATION ALGORITHM

As OFDM/OQAM signal passes through HPA, it will produce severe nonlinear distortion, which degrades the system BER performance. To reduce the nonlinear distortion of OFDM/OQAM signal, the compensation technique of the HPA inverse model in [31] effectively improves the BER performance of the system.

### 3.1 Compensation algorithm of original HPA inverse model

The characteristic expression of the compensator is as follows:

$$f\left(r(n)\right)=\min\left[S,\left|r(n)\right|\right]\left[1-\left(\frac{\min\left[S,\left|r(n)\right|\right]}{A_o}\right)^{2p}\right]^{\frac{-1}{2p}} e^{j\{P(r(n))\}} \quad (8)$$

Where $A_0$ in (8) represents the saturation output point of the amplifier, $S$ represents the best compensation threshold determined by the edge marginal value, which needs to be obtained through multiple simulations.

$$\text{margin}=10\log\left(\frac{A_o}{S}\right) \quad (9)$$

### 3.2 Improved Algorithm

The original HPA inverse model compensation algorithm has the following drawbacks: First, the algorithm only focuses on the receiver and does not reduce the PAPR of the OFDM/OQAM signal at the transmitter. Higher PAPR signals require HPA with larger dynamic range and reduce the working efficiency of HPA and is referred using (9). Secondly, in this algorithm, for different simulation parameters, such as the number of subcarriers and the smoothing factor of the amplifier, multiple simulations are needed to find the most appropriate compensation threshold value $S$, which is not conducive to hardware implementation. To overcome the above shortcomings, this paper proposes a nonlinear distortion compensation algorithm based on clipping and CS. The principle block diagram is shown in *figure 1*.

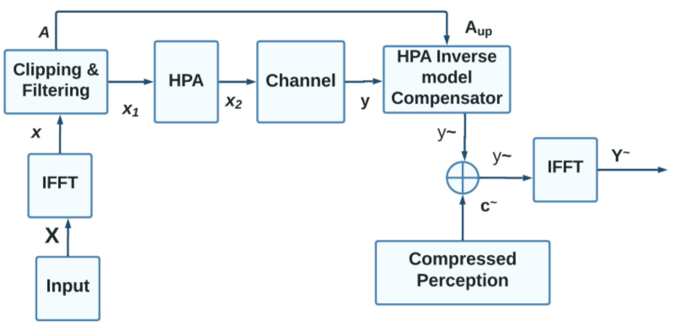


**Figure 1:** Improved non-linear Compressive sensing Technique

#### *3.2.1 Transmitter Processing*

The OFDM/OQAM signals with higher PAPR require HPA with larger dynamic range on the other hand, the work efficiency of HPA is reduced, and on the other hand, HPA will also cause serious non-linear distortion of the signal, leading to a reduction in the BER performance of the system. To improve the working efficiency of HPA and reduce the non-linear distortion of OFDM/OQAM signal, the algorithm proposed in this paper performs limiting processing on the original signal at the transmitting end to reduce the PAPR of the OFDM/OQAM signal. If the original frequency domain signals are $X$, the limiting ratio is $\gamma$, Specific steps are as follows:

*Step 1:* After the original frequency domain $X$ is transformed by IFFT, the original OFDM/OQAM signal $x$ is obtained, that is:

$$x=WX \quad (10)$$

Where $W$ represents the IFFT transformation matrix

*Step 2:* According to equation (6), the time-domain signal $x_1$ after the clipping can be expressed as:

$$x_1=x+c \quad (11)$$

*Step 3:* After the clipping, signal $x_1$ passes through the HPA, the HPA output signal is $x_2$ and is expressed as:

$$x_2=f_{HPA}\left(x_1\right) \quad (12)$$

Where, $f_{HPA}(.)$ represents the nonlinear function of HPA.

#### *3.2.2 Receiver Processing*

After the HPA output signal $x_2$ passes through the channel, the received signal $y$, is as follows:

$$y=Q\,x_2+z \quad (13)$$

Where, $z$ represents white Gaussian noise, and the impulse response matrix of the time-domain channel is $W=WDW^H, D=diag(H)$ and $H$ is the channel response.

If the impulse response matrix $Q$ is known, the signal $y_{re}$ after removing the channel influence is:

$$y_{re}=Q^{-1}y \quad (14)$$

The clipped signal still causes nonlinear distortion after passing through the HPA, the HPA inverse model compensator is first used to compensate the signal to reduce the nonlinearity of the HPA, and then the CS is used to compensate the clipped distortion. In this paper, an improved HPA inverse model is used. The clipping threshold of the transmitter is used to obtain the upper threshold value of the unique corresponding HPA inverse model compensator. It does not need to be selected through simulation, which is beneficial in the hardware implementation. To reduce the complexity of the compensator, the lower threshold was added, and the improvement method is shown in the following *table 1*.

**Table 1.** Comparison of the design methods of the original compensator using (12) and the proposed algorithm compensator thresholds in literature [31]

| | Original HPA Inverse Model Compensation Algorithm | Improved HPA Inverse Model Compensation Algorithm |
|---|---|---|
| Compensator Upper threshold | Yes, it is determined by multiple simulations | Yes, it is determined by clipping threshold |
| Compensator Lower threshold | No | Yes |

The characteristic of the improved HPA inverse model compensator is given by equation (15):

$$f_{comp}=\begin{cases} r(n); r(n)\le A_{down} \\ \min\left[A_{up},\left|r(n)\right|\right]\left[1-\left(\frac{\min\left[A_{up},\left|r(n)\right|\right]^{2p}}{A_o}\right)^{2p}\right]^{\frac{-1}{2p}} e^{j\left|p(r(n))\right|} \\ r(n), r(n)>A_{down}\end{cases} \quad (15)$$

Where, $A_{down}=E\left\{\left|r_n\right|\right\}$ represents the lower threshold of the compensator, and $A_{up}$ represents the upper threshold of the compensator, which is uniquely determined by the clipping threshold $A$, namely:

$$A_{up}=A\left[1+\left(\frac{A}{A_o}\right)^{2p}\right]^{\frac{-1}{2p}} \quad (16)$$

The signal $y_1$ after being compensated by the inverse HPA model is:

$$y_1=f_{comp}\left(y_{re}\right) \quad (17)$$

After the compensation algorithm is adopted at the receiver, the nonlinear effect of HPA is small. Therefore, using the CS algorithm to estimate the clipped noise signal $c_1$, the original time-domain signal $y_2$ at the transmitter is reconstructed, and is as follows,

$$y_2=y_1+c_1 \quad (18)$$

From section 2.2, it is observed that from CS a reliable observation vector *Qs* found, and measurement matrix *F* calculated. In order improve the efficiency of data transmission; this article refers to the method in [25]. The specific steps are as follows

*Step 1:* According to the Bussgang's theory, the frequency-domain signal $X_1$ after clipping is expressed as:

$$X_1(k)=aX(k)+D(k) \quad (19)$$

Where, $X(k)$ in (19) represents the original signal, and $D(k)$ represents the limiting noise that is not related to $X(k)$; $\alpha$ is related to the clipping ratio $\gamma$ and is given by

$$\alpha=1-e^{-\gamma^2}+\frac{\gamma\sqrt{\Pi}}{2}erfc(\gamma) \quad (20)$$

$$\delta_D^2=\left[1-e^{-\gamma^2}-\alpha^2\right]E\left\{\left|X(k)\right|^2\right\} \quad (21)$$

*Step 2:* The maximum likelihood criterion is used to estimate the original frequency domain signal $X_e$, i.e.

$$X_e(k)=\arg\min_{S\in\beta}\left|\alpha^{-1}M(k)-S\right| \quad (22)$$

Where, $\beta$ in (22) represents the signal constellation point set, $M=W^H y_1$, $W^H$ represents the FFT transformation matrix

*Step 3:* As the clipped distortion signal is: $C=(\alpha-1)X+D$, then is given by (23):

$$E\left\{\left|C(k)\right|^2\right\}=\left(2-2\alpha-e^{-\gamma^2}\right)E\left\{\left|X(k)\right|^2\right\} \quad (23)$$

*Step 4:* Determine the selection matrix based on the following formula *S*:

$$\theta_1\approx\left[\frac{\left|H^{-1}\right|^2\delta^2}{\left|H^{-1}\right|^2\delta^2+\delta_D^2}\right]\left(M-\alpha X_e\right) \quad (24)$$

$$T=\left\{k:\left|\theta_1(k)\right|^2<E\left\{\left|C(k)\right|^2\right\}\right\} \quad (25)$$

Where, $\delta^2$ represents the variance of the Gaussian noise signal. If the length of *T* is *L*, then select the corresponding L rows from the identity matrix $I_N$ to form the selection matrix *S*.

*Step 5:* Obtain the observation matrix $Y_s$ and the measurement matrix $\Phi$ from the selection matrix *S*

$$Y_s=SW^HY_1-SX_e \quad (26)$$

$$F=SW^H \quad (27)$$

*Step 6:* According to the observation matrix given in (27) and the measurement matrix, use the OMP algorithm to recover the original signal, such as algorithm 1:

***Orthogonal Matching Pursuit (OMP) Algorithm:***

**1. *Input:*** (1) HPA inverse model compensator output signal $y_1$; (2) observation matrix $Y_s$; (3) measurement matrix *F*; (4) Sparsity: $K=Ne^{-\gamma^2}$

**2. *Output:*** Estimated value of the original frequency domain signal $\bar{Y}$.

**3. *Processing:***

1. Initialization: residual vector $r_o=Y_s$, index $\Delta_0=[\ \ ]$, number of iterations $t=1$;
2. $\lambda_t=\arg\max_{1\le j\le N}\left|\left\langle r_{t-1},\psi_j\right\rangle\right|$ i.e., to find the most suitable index from all columns of the measurement matrix *F*.
3. update the index set $\Delta_t=\Delta_{t-1}\cup\{\lambda_t\}$
4. Update residuals $r_t=Ys-F_{\Delta_t}F_{\Delta_t}^{+}Y_s$, where $F_{\Delta_t}^{+}$ represents the pseudo inverse of $F_{\Delta_t}$, that is, $F_{\Delta_t}^{+}=\left(F_{\Delta_t^H}F_{\Delta_t}\right)^{-1}F_{\Delta_t^H}$; $F_{\Delta_t^H}$ represents the conjugate transpose of $F_{\Delta_t}$.
5. Determine whether the condition $t<k$ is satisfied, if not, $t=t+1$, and return to the second step; otherwise, output $c_1=F_{\Delta_t^H}Y_s$;
6. Estimate the time-domain signal before clipping: $y_2=y_1+c_1$
7. FFT Transformation : $Y=W^Hy_2$

## 4. RESULTS AND ANALYSIS

The Clipping affects the PAPR performance, on the other hand, it can be known from equation (10) that the clipping determines the sparseness of the clipping noise signal and the upper threshold of the compensator. To verify the effectiveness of the algorithm, the performance of PAPR and BER of the algorithm at different clipping ratio $\gamma$ is analyzed. The parameters are as follows:

**Table 2. Simulation Parameters**

| Parameters | Value |
|---|---|
| Modulation | 4QAM |
| No of Subcarriers | 256 |
| IBO | 4 |
| P | 1.8 |

According to equation (10), the sparsity level $K$ of the clipped signal is related to the clip ratio $\gamma$. To ensure the minimum requirements for the clipping noise sparsity, the clipping ratio $\gamma \geq 2.0$, corresponding to the saturation point of HPA. The value is $\gamma_{HPA} = 10^{\left(\frac{IBO}{10}\right)} = 2.5$. Considering the clipping ratio $\gamma$ inside and outside the HPA saturation point, this paper chooses the clipping ratio $\gamma$ =2.2, 2.6 and 3 for analysis. The algorithm's PAPR reduction performance and BER performance are illustrated below.

## 4.1 PAPR Performance

*Figure 2* illustrates that the PAPR of the OFDM/OQAM signal is significantly lower than that of the original signal under the three clipping ratios. CCDF $=10^{-4}$, the $PAPR_0$ corresponding to the clipped signals with clipping ratios of 3, 2.6 and 2.2 are 4.3dB, 3.1dB and 2.1dB, respectively, which is 5% lower than the original signal is7.6 dB, 8.8 dB, and 9.8 dB. It can be found from the simulation results that as the clipping ratio decreases, the stronger the PAPR suppression capability, the smaller the dynamic range of the required HPA, and the higher the working efficiency of the HPA.

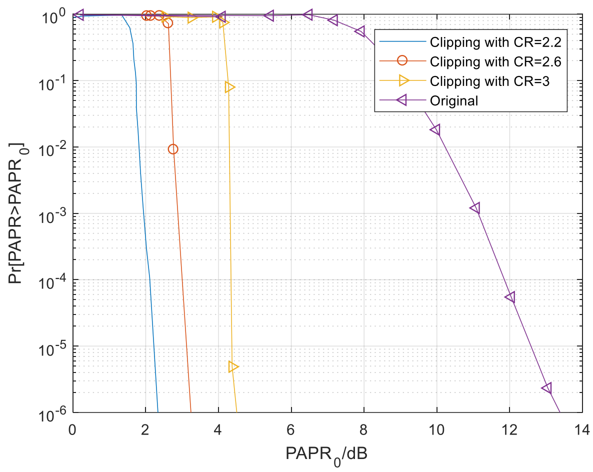


**Figure 2:** PAPR performance analysis of OFDM/OQAM signals under different clipping ratios

## 4.2 BER Performance

In the proposed algorithm proposed, the clipping ratio used by the transmitter directly affects the sparseness of the clipped signal distortion. To verify the effectiveness of the proposed algorithm, under different clipping ratios (*i.e.*, the clipping distortion is to be reconstructed).The BER performance of the proposed algorithm is to be analyzed under Rayleigh channel model, and then a suitable clipping threshold is to be selected for the proposed algorithm.

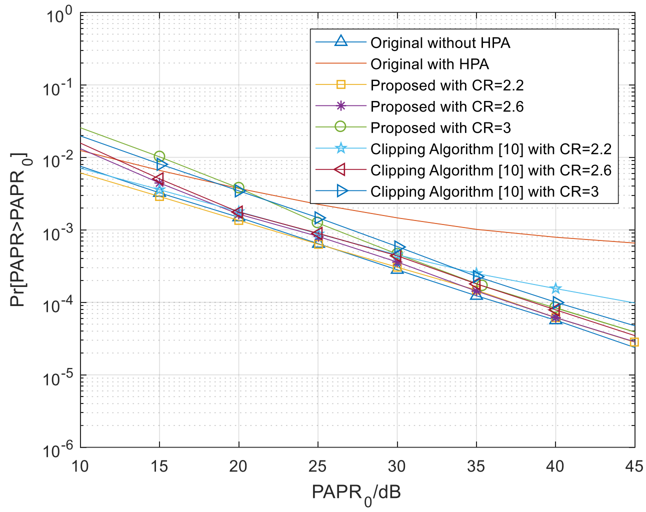


**Figure 3:** BER performance of the Proposed with Existing algorithm under different CR under Rayleigh channel

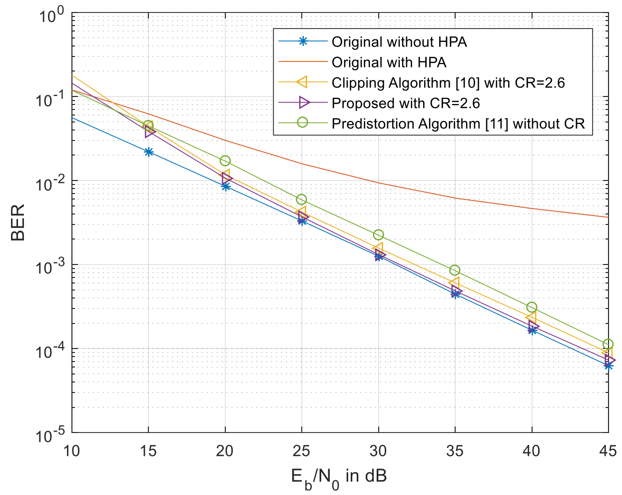


**Figure 4:** BER performance of three algorithms under Rayleigh channel

*Figure 3* shows the BER performance comparison of the proposed algorithm and clipping algorithm in [10] with different clipping ratios, under Rayleigh fading channel. The BER performance of the proposed algorithm is slightly worse than the algorithm in [10], this is because the clipping noise, when the clipping ratio is high is relatively small, the noise impact is relatively large at low SNR, and the corresponding compensation is selected. The upper threshold does not reach the optimal value, but as the SNR is greater than 10 dB, the noise is reduced, and the performance accuracy is improved. The BER performance of the proposed algorithm is gradually better than the algorithm in [10]. At SNR=40dB, with clipping thresholds of the transmitter are 3, 2.6 and 2.2, respectively. The BER of the algorithm in [10] is, $5.6\times10^{-5}$, $9.9\times10^{-5}$ and $1.54\times10^{-4}$ the BERs of the proposed algorithms are $8.4\times10^{-5}$, $6.15\times10^{-5}$ and $6.15\times10^{-5}$. It is observed that under the influence of HPA, the algorithm in [10] cannot obtain better BER performance. Compared with the algorithm in [10], the proposed algorithm with clipping ratios (3, 2.6 and 2.2), the BER decreased by $2.8\times10^{-5}$, $3.75\times10^{-5}$ and $1.1\times10^{-5}$, respectively. In addition, the BER performance of the proposed algorithm under different clipping ratios is significantly different. From the *figure 3* it is observed that the BER performance of the proposed algorithm is better at clipping ratio 2.6.

*Figure 4* shows the BER performance comparison between the algorithms in [10, 11] and proposed. As shown in *figure 4*, at SNR=40 dB, the inverse HPA model compensation method is used without clipping. The BER of [11] is $3\times10^{-4}$. When the clipping ratio is 1.7, the algorithm corresponding to the algorithm in [10] is $2.3\times10^{-4}$, while the algorithm proposed in this paper corresponds to $1.83\times10^{-4}$, compared with the algorithm in [11, 35], the BER of the proposed algorithm is reduced by $0.7\times10^{-4}$. The proposed algorithm effectively improves PAPR reduction and the working efficiency of HPA. Compared with the algorithm in [10], the BER performance of the proposed algorithm is reduced by $0.1\times10^{-4}$.

## 5. CONCLUSION

The conventional HPA inverse model compensation algorithm needs to select appropriate compensation thresholds through multiple simulations, which brings inconvenience to practical applications, and the algorithm does not reduce the PAPR of the OFDM/OQAM signal. The dynamic range required by the transmitting HPA is higher and the working efficiency is low. The algorithm proposed in this paper reduces the PAPR of the OFDM/OQAM signal by clipping at the transmitter. The receiver first uses an improved compensator to compensate for the nonlinear distortion introduced by the HPA, and then uses a compressive sensing algorithm to offset the effect of the clipping noise. The upper threshold of the compensator in the proposed algorithm is uniquely determined by the transmitter clipping threshold. It does not need to be obtained through multiple simulations and is easy to implement. The added lower threshold reduces the computational complexity of the compensator. Simulation results show that the algorithm proposed in this paper effectively reduces the PAPR of the transmitted signal, reduces the dynamic range required by the HPA, and improves the working efficiency of the HPA; on the other hand, it well compensates the nonlinear distortion of the OFDM/OQAM signal and improves BER performance of the system.

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